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Spectral Information Content of the Boreal Forest

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PROCEEDINGS OF THE SEVENTH INTERNATIONAL SYMPOSIUM ON
PHYSICAL MEASUREMENTS AND SIGNATURES IN REMOTE SENSING
COURCHEVEL/FRANCE/7-11 APRIL 1997

Physical Measurements and Signatures in Remote Sensing

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A.A. BALKEMA / ROTTERDAM / BROOKFIELD / 1997

Spectral information content of the Boreal Forest

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ABSTRACT: A major question concerning remote sensing of natural resources in boreal forest regions is the nature of the relationships between spectral reflectance and biophysical information. Regression and model-based analyses were explored to address this question using multispectral data collected from a helicopter platform during the 1994 BOREal Ecosystem and Atmosphere Study (BOREAS) in northern Canada with coincident surface-based biophysical data of boreal forest sites. Potentially useful, simple linear relationships appear to exist between spectral reflectances (primarily visible-red) and biophysical parameters of Aspen; relationships in coniferous canopies (such as Spruce and Pine) are more heavily influenced by their structure and understory, and therefore lack such easily-exploitable correlations. A modified version of the SAIL model incorporating geometric effects of discontinuous canopies, GeoSAIL, was used to assess the role of stand-level structure on reflectance. The structure of the specific tree canopies, significant amounts of shadow, and spectral characteristics of the understory were shown to influence the measured reflectances by varying amounts depending on the canopy. The results of these analyses support stratification of the boreal landscape by cover/species type or some other aggregation prior to retrieval of biophysical parameters as a probable first step in remote sensing of this landscape.

1. INTRODUCTION

A major question concerning remote sensing of boreal forest regions is the nature of the relationships between spectral reflectance and biophysical information. The use of remotely sensed observations for applications beyond assessments of landcover have relied on assumptions concerning the correlations between spectral reflectance data and/or vegetation indices (VI) and vegetation parameters such as leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (f_{APAR}). Regression analysis and model-based analysis using a hybrid vegetation canopy reflectance model, GeoSAIL, were explored to address these assumptions using multispectral data collected from a helicopter platform during the 1994 BOREal Ecosystem and Atmosphere Study (BOREAS) in northern Canada with coincident surface-based biophysical data of boreal forest sites (Sellers et al., 1994). The regression analysis was conducted to address the assumptions of near linearity between spectral reflectance and canopy density. The model analysis was conducted to assess the influence of the heterogeneity of the forest canopy structure and illumination conditions on spectral reflectance.

2. METHODS

Spectral data were collected using an eight channel Modular Multiband Radiometer (MMR) incorporated into the NASA Goddard Space Flight Center/Wallops Flight Facility helicopter-based optical remote sensing system (Walthall et al., 1996). Only the MMR3-visible-red (0.63-0.68 μm) and MMR4-near infrared (NIR) (0.75-0.88 μm) data were used in the analysis. The data were collected from an altitude of 300 m using a 15 degree field-of-view lens while the helicopter hovered over the study sites, yielding an instantaneous field of view of approximately 23 m.

Recorded voltages were converted to at-sensor absolute radiances using procedures described in Markham et al. (1988). The at-sensor absolute radiances were converted to at-surface reflectance factors using Version 3.2 of the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) (Vermote et al., in press) using aerosol optical depths derived from surface-based sun photometer measurements (Markham et al., in press) as inputs. The simple ratio (SR) and normalized difference vegetation index (NDVI) were calculated from reflectances as $(\text{MMR4}/\text{MMR3})$ and as $(\text{MMR4}-\text{MMR3})/(\text{MMR4}+\text{MMR3})$, respectively.

The analysis data sets were restricted to those for "Tower Sites" as these were the focus of detailed, repeated measurements during BOREAS. These sites

consisted of Aspen (*Populus tremuloides*), Jack Pine (*Pinus banksiana*), and Black Spruce (*Picea mariana*) (Sellers et al., 1994). Supplemental data sets that were used in this analysis included measurements of leaf area index (LAI) and canopy architecture parameters, needle and twig optical properties, and understory reflectances. Only LAI was included in the linear regression analysis (N=37), while all of the supplemental data sets were necessary in the model-based analysis (N=25). The simple linear regression analyses was performed on all available tower site data; the GeoSAIL analysis was performed only on those sites where understory data were available. The preliminary processing performed on these data sets is described below.

Measurements of LAI are documented in Chen (in press) and Chen and Cihlar (1995, 1996) using procedures based on measurements of gap fractions and gap size distributions in canopies. Effects of foliage clumping and the fraction of green foliage were also quantified in LAI by means of destructive sampling performed at each site.

Both canopy (needle and twig) and understory reflectances were collected using a Spectron Engineering SE-590 visible-near infrared spectroradiometer; the methods used are described in Middleton et al. (1996) and White et al. (1995), respectively. Needle and twig optical properties were obtained using the methods of Daughtry et al. (1989) and an average value was assumed for each species. Understory reflectances were calculated directly from the digital counts by ratioing target counts with irradiance measurement counts from a reference panel. An observation of each site was made during each intensive field campaign (IFC). Since the SE-590 measures radiance from 0.4 to 1.1 μm (Markham et al., 1995), understory and canopy measurements were integrated to the bandwidths of MMR3 and MMR4.

3. REGRESSION ANALYSIS

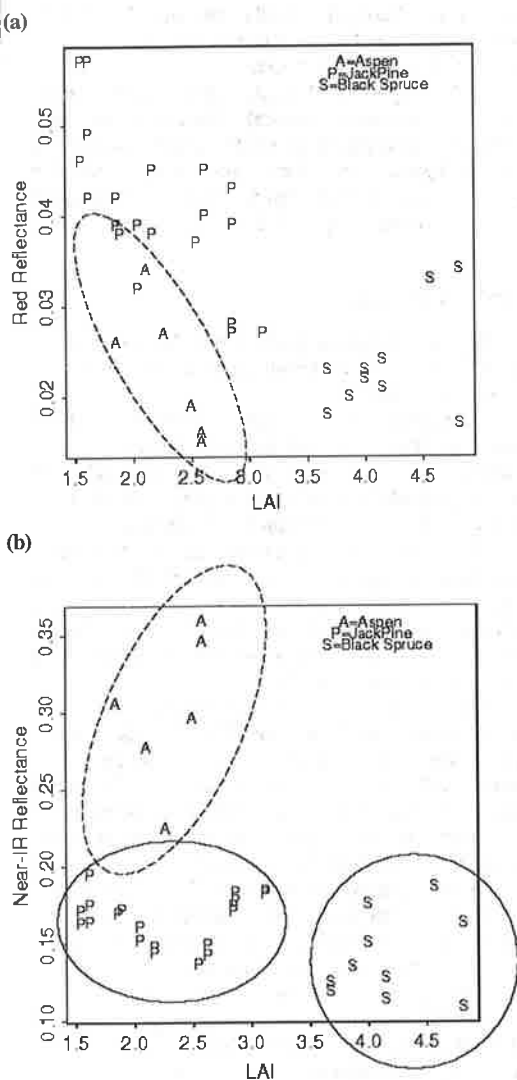
Results of the linear regression analyses of LAI (X) to VIs and reflectances (Y) show the amount of variability in canopy reflectance explained by changes in LAI (Tables 1 and 2). For the data set as a whole, r^2 values in the VI regressions were low, ranging from 0.003 for the SR and 0.11 for the NDVI to 0.38 for MMR3 and 0.10 for MMR4.

When stratified by species, the better performance of simple linear relationships in the reflectance regressions at the Aspen sites and poor performance at the conifer sites, especially in the Black Spruce, can be seen (Figures 1 a and b). The Aspen LAI showed a negative relationship with the MMR3 and a positive relationship with the MMR4 data, which maximizes the utility of the vegetation indices, with r^2 values of 0.62 and 0.21, respectively. The Jack Pine sites performed reasonably well in the relationship of LAI to MMR3 ($r^2=0.50$ with a negative slope), although the relationship of LAI to MMR4 ($r^2=0.0$) showed

Table 1: Regression Analysis of VIs and Canopy LAI by Species. Tower Sites Only						
Predictor Variables						
N	SR (r^2, slope, offset)			NDVI (r^2, slope, offset)		
	All					
37	0.003	0.27	5.8	0.11	0.04	0.58
	Aspen					
6	0.58	17.0	-24.0	0.46	0.14	0.53
	Pine					
21	0.46	1.45	1.1	0.42	0.1	0.42
	Spruce					
10	0.14	-0.8	9.5	0.14	-0.03	0.85

Table 2: Regression Analysis of Reflectances and Canopy LAI by Species: Tower Sites Only						
Predictor Variables						
N	MMR3 (r^2, slope, offset)			MMR4 (r^2, slope, offset)		
	All					
37	0.38	-0.01	0.05	0.10	-0.02	0.24
	Aspen					
6	0.62	-0.02	0.07	0.21	0.08	0.13
	Pine					
21	0.50	-0.01	0.07	0.00	0.00	0.16
	Spruce					
10	0.24	0.01	0.00	0.06	0.02	0.08

substantial scatter. Thus, we observed a decline in the predictive ability of the SR and NDVI in spite of an increase in the number of observations in the regression relative to the Aspen. The linear relationships performed poorly at the Black Spruce sites as well. The scatter for the MMR3 and MMR4 plots with LAI is sufficient to mask any obvious trend in the relationship. Similar confusion is shown in the vegetation indices, with a reduction of Black Spruce sites to r^2 values of 0.14 for both SR and NDVI. We conclude that little of the variation in reflectance over the Black Spruce can be explained by LAI variations alone. These trends in the tower site data were supported in the results of an analysis of the data over all sites (tower and auxiliary sites) given in Loechel et al. (in press).



Figures 1 a and b: LAI vs. Helicopter-Measured Canopy Reflectances in the red (a) and NIR (b) at Aspen (A), Spruce (S), and Pine (P) sites.

4. GEOSAIL MODEL ANALYSIS

Given the poor performance of LAI relationships in explaining the variability of the conifer stand reflectances, a hybrid scene radiation model was used to assess the contribution of other stand variables. A modified version of the SAIL (Verhoef, 1984) model incorporating geometric effects of discontinuous canopies, GeoSAIL, has proved to be a useful tool for assessing the sources of variability in forest stand reflectance

(Huemmrich, 1995). GeoSAIL uses the turbid media radiative transfer solution of the SAIL model coupled with the geometric model of Jasinski (1990) to simulate reflectance from discontinuous canopies. Endmember reflectance of the scene components (sunlit crown, sunlit background and shaded background), are calculated. Full scene reflectance is then calculated using a weighted sum of these components depending on the percent cover of the stand. Inputs to the model include measurements of optical properties of the understory and canopy (twigs and needles), LAI, leaf angle distribution, percent cover, percent green-to-total foliage area, and view and solar geometry. A cylindrical tree shape was assumed at all sites. Spherical and planophile leaf angle distributions were assumed for needles and branches, respectively (Huemmrich, 1995). Only conifer stand data where understory reflectances were available were addressed with this analysis.

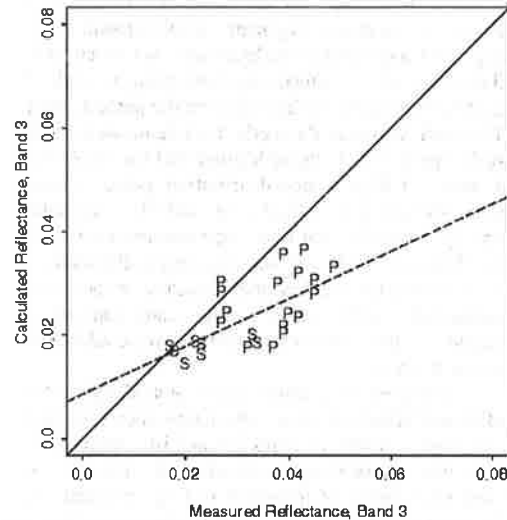
The GeoSAIL simulations are plotted against the MMR3 and MMR4 spectral reflectances measured with the helicopter system (Figures 2 a and b). Above each plot are two regression equations which describe: (1) the plotted relationship of measured (X) vs. modeled (Y) reflectance in the given band, and (2) the regression of LAI (X) vs. reflectance (Y) of the same data ($N=25$). In each band, the relationship between modeled and measured reflectances fell near the 1:1 line. The relationship of simulated and measured red reflectances showed greater scatter and a trend away from the 1:1 line at higher values. For MMR3 reflectance, the percentage of variation explained by the GeoSAIL model ($r^2=0.43$) is less than that explained by the LAI-Regression model ($r^2=0.51$). Almost none of the variation in reflectance was explained by LAI alone ($r^2=0.05$) in the MMR4 conifer regression model. Variation explained in that data set increased with the inclusion of understory, canopy closure, shadow and background reflectance, and view and illumination geometry, as indicated by the relation between measured and GeoSAIL modeled reflectances ($r^2=0.42$).

5. DISCUSSION

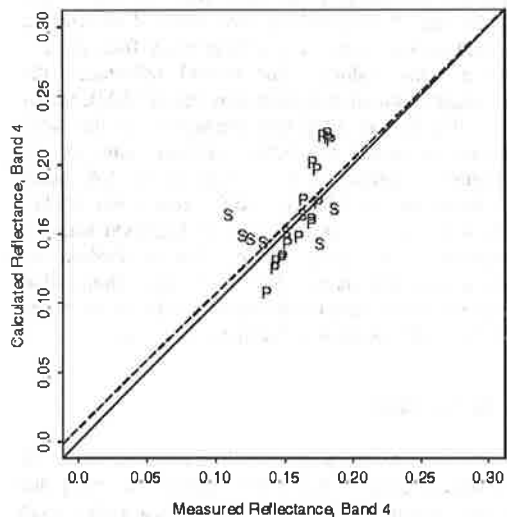
The Aspen sites exhibit traditional trends of spectral reflectance relationships with LAI probably due to the correlation of LAI with percent cover often present in deciduous canopies. Some effects of Aspen scene structural influence on reflectance are evidenced by the low r^2 values indicating that LAI alone does not explain the NIR reflectance.

The conifer site red and NIR reflectances appear to be heavily influenced by factors other than LAI, which may be attributed to the "clumped" nature of conifers decoupling LAI from percent cover. Thus, in conifers, percent cover, background reflectance, and shadow (determined by illumination and viewing geometry) make important contributions to scene

(a) MMR3-red regression results:
 Modeled vs. Measured: $Y = 0.46X + 0.01$; $r^2 = 0.43$
 Measured vs. LAI: $Y = -0.01X + 0.05$; $r^2 = 0.51$



(b) MMR4-NIR regression results:
 Modeled vs. Measured: $Y = 0.97X + 0.01$; $r^2 = 0.42$
 Measured vs. LAI: $Y = -0.01X + 0.17$; $r^2 = 0.05$



Figures 2 a and b: Measured (X) vs. Modeled (Y) Canopy Reflectances in the red (a) and NIR (b) at Spruce (S) and Pine (P) sites.

heterogeneity. The increasing departure of GeoSAIL simulations from the MMR3 measurements at higher values suggests that the absorption-dominated endmembers of the scenes (shadow and hence associated geometries of tree shape), and the amount of background reflectance present may be under represented and are in need of examination. The high degree of correlation

between the GeoSAIL simulations and the MMR4 measurements emphasizes the importance of structure and multiple scatter in the scene.

A study by Hall et al. (1995) used this same model to decompose spectral reflectance data into endmembers of sunlit crown, shadowed background, and sunlit background and found a promising relationship between shadow and LAI that was better than the sunlit endmember relationship with LAI.

6. CONCLUSIONS

1. Simple relationships appear to exist between spectral reflectances and LAI of Aspen: negative with visible-red and positive with NIR.
2. Reflectance from coniferous canopies, such as Spruce and Pine, are more heavily influenced by their structure and understory, and lack the traditional easily-exploitable correlations of Aspen. Specifically, a positive NIR-LAI relationship is not apparent.
3. The heterogeneity of the structure of the specific tree canopies, significant amounts of shadow, and spectral characteristics of the understory were shown to influence the measured reflectances in the NIR. However, some variability in the NIR is still found and the red trend varies from the 1:1 line.
4. The comparison of simulations with the measurements shows that a model such as GeoSAIL is appropriate to describe the reflectance of the scene. Further refinements to the inputs and the model assumptions, such as the more accurate representation of tree shape and mutual shadowing effects among trees, would most likely improve the results.
5. Reliable retrieval of conifer LAI will have to rely on something other than a linear LAI-NDVI relationship, as LAI alone is insufficient in accounting for a majority of the variability in canopy reflectance.
6. Stratification of the boreal landscape by cover/species type or some other aggregation prior to retrieval of biophysical parameters as a probable first step in remote sensing of this landscape.

Acknowledgments. The authors gratefully acknowledge the contributions of all of the BOREAS field staff, including those working on BORIS. Specifically, we thank the helicopter crew and technical support involved in surface biophysical and radiometric measurements. The funding for this research was provided by NASA Grant #NAG52308. Manufacturer names are given for information purposes only and do not imply endorsement.

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